ARMY RESEARCH LABORATORY

Critique of "An Analysis of the Blast Overpressure Study Data Comparing Three Exposure Criteria," by Murphy, Khan, and Shaw

by G. Richard Price

ARL-CR-657 August 2010

prepared by

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Charlestown, MD 21914

NOTICES

Disclaimers

Army Research Laboratory

Aberdeen Proving Ground, MD 21005-5425

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14. ABSTRACT
Murphy et al. analyzed the performance of MIL-STD-1747D, L_{AEQ8}, and the Auditory Hazard Assessment Algorithm for Humans (AHAAH) model as they predicted outcomes on the Albuquerque studies (AS) data set. Unfortunately, they erred in several invalidating ways. First, they overlooked underlying nonlinearities in the hearing protector (which rendered the AS data set unique, the use of MIL-STD-1474D invalid, and the L_{AEQ8} calculations useless outside the data set). They overlooked the nonlinear conductive path of the ear that, at the very high intensities, greatly affected the energy reaching the cochlea (which implies that their L_{AEQ8} analyses measured under the muff cannot be usefully extrapolated outside the data set). Their analysis of L_{AEQ8} under the protector did establish that a criterion level of 110-dB L_{AEQ8} fits the data, but they failed to comment on the discrepancy between this level and the 85-dB L_{AEQ8} criterion that is traditionally used. Further, they misapplied the AHAAH model in using the “unwarned” calculation and overlooked the model’s capacity to predict the effect on different percentiles of the population. Their analysis indicated that the “warned” calculation with the AHAAH model did rank hazard acceptably for the 95th percentile ear, and we note that it did so for small arms fire as well, all without adjustment. More research in the pressure regime between 115 and 160 dB is needed for the development of a comprehensive damage risk criterion for intense noise.

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1. Introduction

Murphy et al. (2009) purport to analyze the Albuquerque studies (AS) data with five variants of three different damage risk criteria (DRC) and then examine the predictions with an array of statistics. Paradoxically the authors claim that (1) their work has not addressed the actual determination of a risk threshold and (2) the article has laid the groundwork for such a determination. These statements misrepresent what they actually did and suppress what we believe to be an important finding in this work that speaks to the determination of a risk threshold. The report also criticizes existing and proposed DRCs; hence, good scientific discourse requires that its contentions be addressed. Perhaps most dangerous from the standpoint of hearing conservation is the fact that the authors, while claiming that they have not addressed determination of a risk threshold by their uncritical use of an L_{AEQ8} measure at these very high levels, appear to invite the use of an L_{AEQ8} criterion for very intense sounds. Evidence suggests that the unqualified use of such a measure could have disastrous consequences for hearing conservation.

We believe that the two claims are misleading, and that the assessment of how well the different criteria characterize the AS data set, in spite of their intensive use of statistical analysis, nonetheless contains serious invalidating errors. In essence, the authors have ignored physical and physiological constraints underlying the data, which have major impacts on the interpretation of their findings. Furthermore, they deliberately fail to consider the relationship of their analysis of the AS data to other gunfire data sets; this failure obscures the major implications of their findings for DRC development. Finally, they have mischaracterized and misapplied the DRCs they are testing.

In this report we will first discuss the AS experiments in order to cover the approach used in them, and then we'll explore some of the details that are critical to their interpretation, especially as they interact with the analysis conducted by Murphy et al.

2. The Albuquerque Studies

The AS data set is the most extensive set of studies of impulse noise exposure of protected ears ever undertaken (Johnson, 1994, 1998; Patterson et al., 1997). The studies were well-conducted and documented far more completely than previous work. The AS represents the greatest source of data on protected human exposure to intense impulses of which we are aware. In the AS, the exposure pressures were far higher than in most studies, higher even than those around modern weapon systems—as high as 195-dB peak pressure level

(PPL). Given the difficulty and cost in conducting such research with human volunteers, it seems unlikely that this database will be superseded in the foreseeable future.

There were, however, a number of surprises during the study that affected the essential design of the experiments and their interpretation. Fortunately, the study was documented well enough that the effects of these unusual situations are for the most part known. We will consider first the essential design of the study and then comment on the features that warrant special attention.

2.1 Design of the Studies

The design of this series of studies was based on the concept that exposure to impulses produced by exploding C4 charges of differing weights and physical locations would simulate exposures to generic large-caliber weapons used by the U.S. Army. The exposure scheme was laid out as diagrammed in table 1. Each level of the exposure was intended to be a 3-dB increase in the peak pressure of the impulse (a doubling of its energy), and within a level, the number of impulses was increased in steps that doubled in energy.

Table 1. Exposure matrix for the AS.

	No. of Impulses				
Level	**6**	**12**	**25**	**50**	**100**
7		x	x	x	x
6					
5					
4					
3					
2					
1					

A particular exposure was considered dangerous for a subject if it produced a 25 dB or greater threshold shift at any audiometric test frequency. This was referred to as a “full audiometric failure.” In practice, however, if a 15- to 24-dB threshold shift was produced at a particular level, the experimenters were unwilling to expose that ear to the next higher level. In such a case, a “conditional failure” was recorded at a less energetic level.

Subjects entered the exposure matrix (table 1) at the lower-left corner (level 1, six impulses) wearing a circum-aural hearing-protective device (a Racal muff). If they had no significant threshold shift, they progressed to the next higher exposure, level 2, six impulses, and so on, up the left side of the matrix, as indicated by the up arrow. When they reached level 7, six impulses, and passed it, they dropped back to level 6 and were exposed to increasing numbers of impulses, as indicated by the right-pointing arrow. If they received no significant threshold shift, they were exposed to the next higher number of impulses. If they reached level 6, 100 impulses, they had successfully completed the course of exposures. If, however, during the course of traveling this path, a subject experienced a conditional failure or a full audiometric failure, he was dropped to a less energetic exposure (down one or two levels, respectively) and moved toward more impulses at the lower level and so on.

In the initial conception of the study, it was presumed that failures would occur as the levels increased, and that the subjects would “migrate” on a “just safe” path through the matrix at lower levels and increasing numbers of impulses. A recent analysis of the individual data indicates that this apparently reasonable expectation was not met during the exposures (Price, 2010). Of 28 subjects (Ss) who experienced a conditional failure or a full audiometric failure, 25 went on to safely experience higher levels of exposure, many much higher. It was also presumed, on the basis of existing DRCs, that double hearing protection would be needed in order to complete the matrix; however, it did not turn out to be necessary. In fact, the ear appears to be surprisingly robust, and such failures occur less often than predicted by existing standards. As a result, only a few subjects were tested on the interior cells of the matrix (levels 1–5 and 12, 25, 50, and 100 impulses), and the data there are only suggestive.

2.2 The Exposures

The free-field impulses were designed to be Friedlander-like impulses, characteristic of Army weapons. The apparatus necessary to produce these impulses took two different configurations. The exposure referred to in the reports as the 5-m conditions had a bare charge suspended about 3 m above a concrete pad, 5 m from the subjects. For the 3- and 1-m exposures, a mortar-like exposure device was fabricated, and the subjects were seated on a circular expanded metal platform with their ears just above the level of its “muzzle,” about 3 m above the ground. The subjects were located either 1 or 3 m (approximately) from the edge of the barrel, hence the designation 3- and 1-m conditions. In acoustic terms, the A-durations of the impulses were about 2.6, 1.5, and 1.0 ms for the 5-, 3-, and 1-m conditions. The pressure histories of the impulses and their energies have been reported in Patterson et al. (1997) and in figure 3 of Chan et al. (2001).

The subjects were seated during all exposures with their heads in a chin rest and their right ear facing the impulse source. The nontest ear (typically the left ear) always wore double hearing protection. Impulses were delivered 1 min apart, following a countdown (10, 9, 8, 7…) that was audible because of a peak-limiting talk-through circuit in the muff. Subjects were well aware of when the impulse was coming and, in fact, depended on the countdown. In one test, a set of trials was attempted without the preparatory countdown, and subjects were unwilling to tolerate the higher exposure levels without warning to prepare them for the impulse.

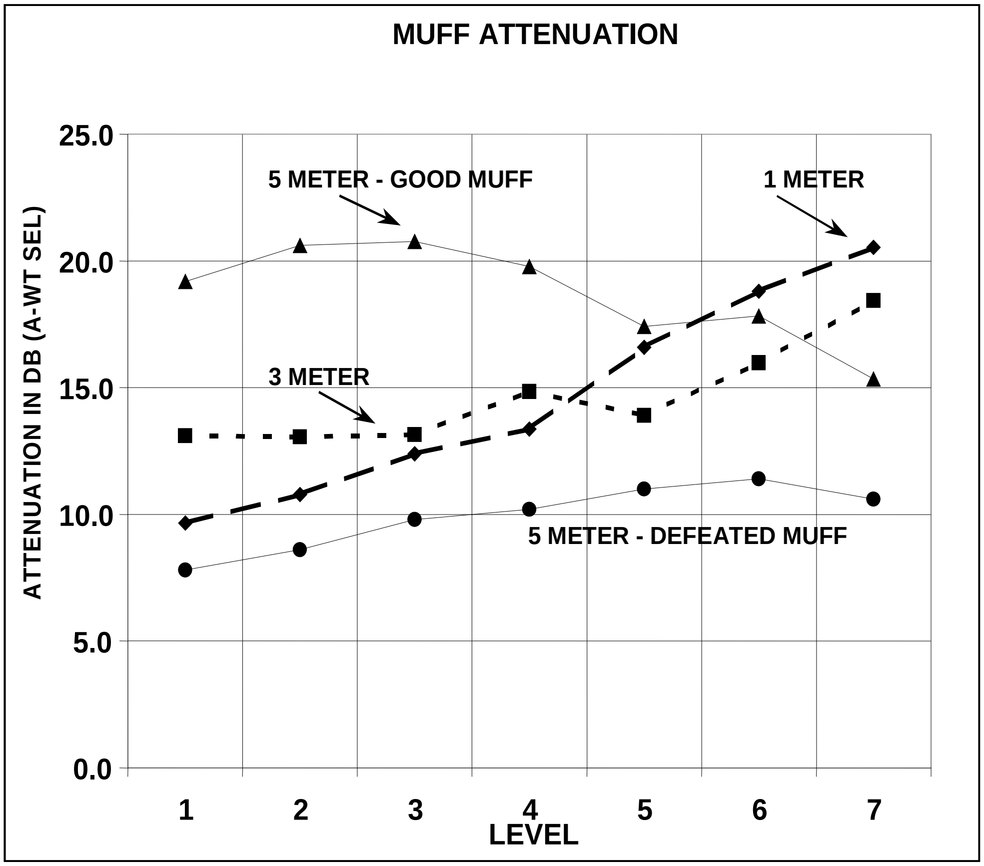
2.3 The Hearing Protector

The Racal muff was chosen originally because it represented a moderately effective hearing protector that had a talk-through circuit and could be worn under an infantry helmet (used in the tests). And it was possible that when the pressures rose to the point that it did not provide adequate protection, an earplug could be added and exposure continued. The unexpected result from the first 5-m study was that the muff alone provided adequate protection for all subjects. MIL-STD-1474D had predicted that double hearing protection would not be adequate. The experimenters then made a critical decision. The seal on the right muff (toward the impulse source) was defeated by inserting eight plastic tubes (2.3-mm inside diameter, four open to the front, and four open to the rear). This leak was intended to simulate a badly fitting ear seal and perhaps more closely replicate the fit under field conditions. The 5-m study was rerun with these muffs, followed by the 3- and 1-m conditions.

3. Problems With the AS

3.1 Nonlinear Hearing Protective Devices and Free-Field Exposures

The Racal muff exhibited unexpected behavior. Conventional wisdom was that passive hearing protectors are essentially linear devices with respect to level, i.e., measured attenuation is independent of level. In contrast, at these very high levels, the modified muff was nonlinear with respect to amplitude, i.e., its attenuation increased as a function of level. In contrast, the attenuation of the unmodified muff was 5–6 dB less at the very highest sound pressure levels. These points are illustrated in figure 1 where the attenuation at each level is plotted (A-weighted sound exposure level under the muff was subtracted from the A-weighted SEL in the free field). Free-field peak pressures changed ~18 dB in 3-dB steps from levels 1 to 7. Under the muff, however, pressures rose 7.2 dB (1-m data), 11.6 dB (3-m data), 12.2 dB (5-m data), or 18.9 dB (5-m good muff).



Note: Free-field SPLs increased 3 dB for each change in level. Peak free-field pressure for level 1 was 179 dB for the 1-m condition, 178 dB for the 3-m condition, and 173 dB for the 5-m condition.

Figure 1. Attenuation of the earmuffs used in the AS as a function of the exposure level. (Data is from Patterson et al. [1997], calculated from pressure histories distributed on a CD. Figure is from Price [2007].)

In the same vein, Murphy et al. (2009) have included a figure (their figure 14) that combines all the specific responses for the modified muff, but which makes the same essential point (see figure 2 in this report). They claim to have plotted peak level reduction, yet the labels indicate L_{AEQ8} data were actually plotted, rather than peak levels. They are different quantities, and combining the data may obscure some detail, yet the increase in attenuation with higher levels is clear and is a major contaminant of the data.

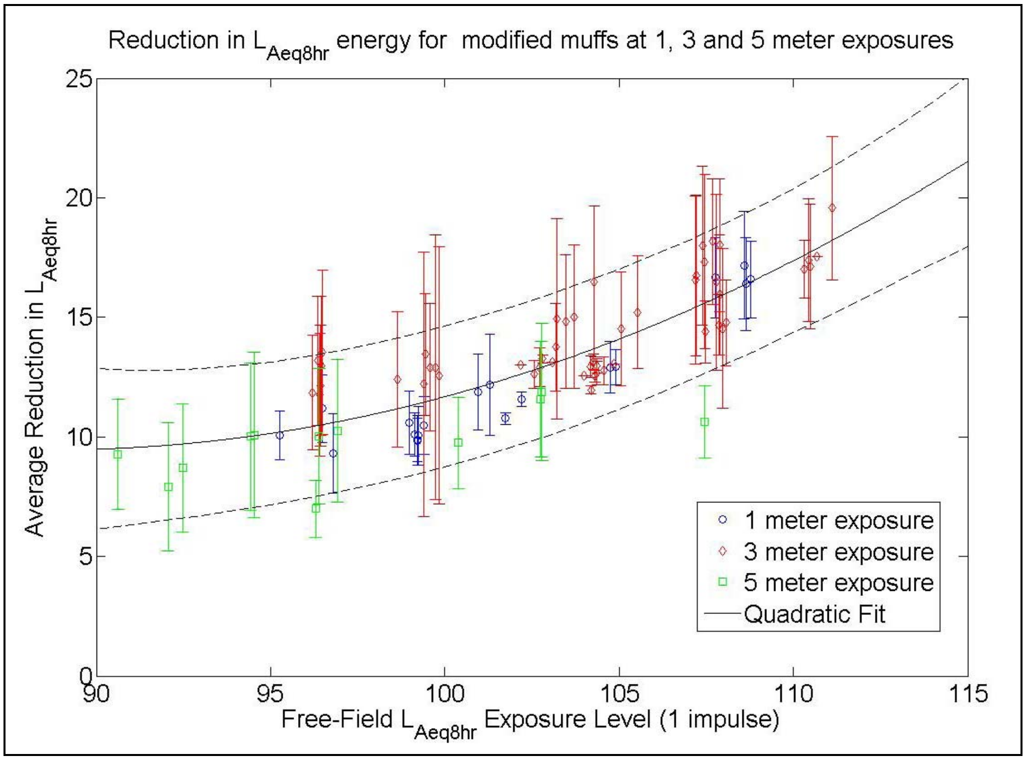


Figure 2. Figure from Murphy et al. (2009) demonstrating the nonlinearity of modified muff performance. Their caption reads as follows: "Comparison of the reduction in $L_{AEQ8}hr$ from free-field to underneath the modified RACAL earmuff. The average and standard deviation of the *peak impulse reduction* measured between the free-field probe and the protected microphone were determined for each set of impulses. The different exposure distances are denoted by circles for 1-m, diamonds for 3-m and squares for 5-m exposure distances. A quadratic fit is shown to illustrate the trend of the *peak reduction* with increasing free-field *peak level*." (Emphasis added, see text for explanation.)

The HPD used in the AS thus had a major effect on the acoustic exposure—the independent variable—in the AS. Any standard or analytical technique that bases its assessment on pressures measured in the free field obviously misses this detail in these data. On this basis, the analyses by Murphy et al. with MIL-STD-1474D and with the free-field L_{AEQ8} data is confounded by the action of the muffs and is obviously only applicable to this specific data set and not in situations in which normal HPDs are worn. Though they have appreciated the problem, as their figure indicates, they do not seem to have grasped the implications for their analytical approach. We note that they were not alone in making this error. Chan et al. (2001) did the same thing almost 10 years earlier, and this problem was noted at that time (Price, 2003).

In view of the foregoing, it is ironic that Murphy et al. found that "generally, the free-field data for L_{AEQ8hr} provided a better fit to the BOP injury data compared to the protected data." Such a finding has the superficial appearance of certainty wrapped in a statistical blessing. But when the underlying issues regarding the variable attenuation of the muff are examined carefully, we see that analyzing the data without concern for the energy actually arriving at the ear has in fact led to a confounded and inaccurate conclusion.

3.2 Limited Reports of Exposure

A second concern is that we have no full exposure measured under the muff for an individual subject. We are fortunate to have the sample recordings distributed with the Albuquerque reports; however, it is not possible to follow a full exposure for any individual subject. The interest in doing a full analysis of the subjects' exposures is a function of the potential for unique circumstances in the fit of the protector or the pressure history of a specific impulse to have large effects and impact the data disproportionately. By way of illustration, with impulses at these levels (as high as 195 dB peak), the forces imposed by the acoustic wave are considerable. A picture in a report by Johnson and Patterson (1993) shows a muff (one not used in the experiments) to have been lifted entirely off a manikin head about 40 ms after the initial wave front arrived. Levels above 180 dB are truly intense noise exposures and have the ability to produce unexpected effects, such as the nonlinearity in figure 1 or movement of the muffs during the exposure (actually observed in the tests [Johnson, 1994]). Estimating the effect of 50 or 100 impulse exposures for more than 300 subjects based on data from five or six impulses includes considerable uncertainty. Change in hearing at these levels sometimes occurs very suddenly, as though one impulse were particularly bad (Johnson, 1999).

It is also true that sound fields around explosive sources can have occasional "hot" spots. A recent analysis of the AS data set has found that even within the data we have, there are several examples of individual impulses being potentially much more "damaging" (3–5 standard deviations above the mean hazard) than the other impulses at a given level (Price, 2010). Given the possible importance of such "rare events," it would have been interesting, even critical, to have full recordings of the exposures.

3.3 Generalizability of the AS

It would be imprudent to generalize from the AS to the hazard of weapon noise because the conditions tested fall far short of representing real weapon exposures. Consider first the subjects and the muffs. As we have seen, the modified muff was obviously a unique device. There is, of course, neither such a thing as a "generic protector" nor any way to create a modification that correctly simulates "field fit" under all conditions. In fact, for dismounted infantry in combat, it is virtually certain that a plug will be worn rather than a muff. It is also true that all leaks should not be thought of as equal in their effect. For example, hole size and orientation could make a protector both amplitude and azimuth sensitive. Further, there is serious concern that in the experiments the protectors were carefully fitted to the subjects, and they were always exposed in a specific orientation to the impulse source (ear was facing the source, holes in muff at grazing incidence). In practice, rigid control of impulse presentation cannot be achieved in training and certainly not under combat conditions. Lastly, given the relatively high energies that were demonstrated to be tolerable in these tests, it might be tempting to assume that details with respect to hearing protection "don't really matter" or that just any protector or modification of a protector is okay. Such assumptions would be disastrous.

The impulses did, to a first approximation, resemble those generated by real weapons. However, the noise field around weapons is complex and, because of reflective surfaces, may have unique features in every deployment. Coupled with the fact that the orientation of the Soldier is not fixed, real exposures are much more variable than the exposures in the Albuquerque studies. For example, the ground reflection of the impulse is always present for weapons fired in the open, yet because of the different geometry of the exposure situation, it was very much reduced in the 1- and 3-m exposures. Or in the case of real weapons, there is usually considerable unburnt propellant at the muzzle. Given hot propellant in a turbulent cloud coupled with the sudden availability of oxygen, there may be occasional "hot spots" in the noise field due to secondary combustion where the pressures might be 10 or more dB higher than the impulse from the muzzle.

Lastly, the rate of fire in these studies was slow, about 1 impulse/min. Soldiers are capable of firing weapons, such as the 105-mm howitzer, about once every 3 s or 20 rounds/min (Paragallo and Dousa, 1979); Gatling gun-type weapons can fire several thousands of rounds per min. No one study can do everything, but the rate of fire variable has not really been explored.

4. Another Nonlinearity: The Conductive Path

There is an additional nonlinearity inherent in the suspension of the stapes, which controls input to the cochlea. This nonlinearity confounds all criteria that do not take specific account of it. The problem was observed long ago by von Bekesy (1936) and later by Huttenbrink (1988). The nonlinearity was measured by Guinan and Peake (1967) in the cat, and the implications for DRCs were noted by Price (1974). In order to accommodate this aspect of the ear's anatomy, a nonlinear stapes element was specifically modeled in the Auditory Hazard Assessment Algorithm for Humans (AHAAH) (Price, 2006; Price and Kalb, 1991). We believe that the success of the AHAAH model in predicting hazard is largely due to this element.

In essence, the nonlinearity is due to the fact that the stapes suspension (annular ligament) stiffens when displacements rise, and this limits the transmission of energy to the cochlea. The physical constraint on the stapes displacement has effectively created a peak clipping element operating in the time domain. The problem for the interpretation of the analysis by Murphy et al. is that they fail to recognize that this nonlinearity is an integral part of all the experiments included in the AS data set. When you use measures, such as A-weighted energy measured in air at very high SPLs, the energy arriving at the cochlea is no longer simply related to the pressure in air. In contrast, at very low pressures, a 6-dB change in air would produce a 6-dB change in the cochlea, but at very high pressures the change might only be a decibel or two, depending on the details of the displacement history of the stapes. If DRC algorithms are to succeed, they must reflect these nonlinearities. Other than the AHAAH model, none do.

5. An A-Weighted Criterion?

In the paper, Murphy et al. confuse issues in their use of the L_{AEQ8} metric. They refer to an A-weighted energy criterion, but they do not use the concept. A-weighted energy is a measure and not a criterion. It becomes a criterion when it is given a specific value; 85-dB L_{AEQ8}, being the one most commonly used, is applied as a limit. This is a small point, but one that pervades the article and leads the authors to miss their main finding—namely, that an L_{AEQ8} of 85 dB grossly overpredicts the hazard for the AS data set.

The analysis by Murphy et al. does establish that an A-weighted energy measure taken under the muff (nonlinearity of muff accounted for) fits the AS data for hearing loss at about a 110-dB L_{AEQ8}. We believe that this finding is critical. Considering the import for the development of DRCs, it is baffling that they fail to discuss the disparity between the A-weighted level that fits the AS data set and the criterion level that has been reported to fit for small arms fire (about 85-dB L_{AEQ8}) (Dancer, 2000; Price, 2007).

The authors specifically state that they do not attempt to draw conclusions outside of the AS data set; however, failure to follow the implications of this solid finding could mislead others into seeking a single-valued L_{EQ}. There is a modest amount of data on small arms (admittedly mostly from an earlier era), but it is well documented. The present DRC, MIL-STD-1474D, was based on just small arms data, and this work has been published at some length (Coles et al., 1968). Additional data have also been produced (Hodge and associates, 1964, 1965, 1966; NATO Research Study Groups, 1987, 2000; Pfander, 1975). The French standard for impulse noise was an 85-dB L_{AEQ8} (up to 160-dB PPL), and the AHAAH model agrees reasonably well with this number for small arms (Price, 2007). Even when allowances are made for reasonable uncertainties with the data set, the 25-dB disparity in hazard level between small arms exposure and large caliber–type impulses in the AS data is large enough that we can be confident that A-weighted energy predicts very poorly at these high levels. On top of that, the size and direction of this disparity makes excellent physical and theoretical sense when the nonlinearities in the ear's conductive path are considered.

The disparity is arguably even greater if one picks a test impulse that puts most of its energy where the ear conducts best. If one uses the AHAAH model to calculate the hazard from the impulse from a primer (Price and Wansack, 1989) presented in the free field (spectral peak at about 3.0 kHz) at 155 dBP to a subject who does not know it is coming (no middle ear muscle protection), then for that condition, an exposure to an L_{AEQ8} of >71dB is calculated to be just safe. If we assume that the model is valid for the primer impulse, an L_{AEQ8} between 71 and 110 dB might be appropriate for firearms impulses, depending on the details and level of the impulse. Even when allowances are made for uncertainties in data sets, the inadequacy of an A-weighted measure as a really solid finding has not been properly dealt with in the paper by Murphy et al.

We conclude that the data clearly agree that an 85-dB L_{AEQ8} might work fairly well for lower sound pressures; however, it clearly does not do so at higher SPLs. And because of the basic nonlinearity in the conductive path to the cochlea, it is irrational to contend that it could work over the range of pressures encountered.

In this regard, we find it interesting to note that the AHAAH model does include the relevant nonlinearities and manages to predict a hazard for both small arms and the AS data set without adjustment.

6. Inappropriate Uses of the AHAAH Model

Models are created with certain basic premises inherent in their structure, and fair treatment requires that they be used as intended. If a model is used in ways that violate the premises embedded in it, then it is hardly reasonable to criticize the model when it fails to perform well.

In three cases, Murphy et al. misused the AHAAH model. In one set of calculations they used both full audiometric failures (>25 dB threshold shift [TS]) and conditional failures (15 < TS < 25 dB) as the dependent variable. The AHAAH model, as they used it, was designed to predict a 25-dB TS (500 auditory risk units [ARUs]) for a 95th percentile ear for each exposure impulse. To model the onset of a 15-dB TS in the 95th percentile ear, the risk level would have to have been dropped to 340 ARUs. They did not do this, and as a result, the model appears insensitive.

The second problem is also related to the first. The AHAAH model, as they used it, was designed to replicate the behavior of the 95th percentile ear. Their statistic plotted the audiometric shifts of the whole population of subjects, who were not, of course, all 95th percentile ears. The AHAAH model appears to overpredict hazard when one compares the percentage of a population showing some change. One could, using the model, generate predictions for a normal population of any percentile of susceptibility, but that is not the comparison they used. In this case the AHAAH model was simply misused.

It was also a misuse of the model to do an “unwarned” calculation. The model is designed and calibrated based on the assumption that there is a difference in middle ear muscle activity between warned and unwarned exposures. If there was ever an exposure population that qualifies as “warned,” it was the Ss in the AS. The impulse, from the standpoint of the Ss, was very intense—they really wanted to know when it was about to arrive. The experimenters in the AS specifically chose the HPDs to have a talk-through provision that allowed the Ss to hear the countdown to the impulse. It was this case for which the “warned” calculation was intended, as the instructions with the model clearly indicate. Murphy et al. might wish to debate the details of the middle ear muscle contraction in the AHAAH model; however, doing an unwarned calculation and then analyzing it is a misuse of the model.

7. Inherent Uncertainties in the AS Data Set Limit Statistical Certainty

Murphy et al. have gone to great lengths to achieve statistical certainty regarding the information in the AS data. The desire for certainty is laudable, yet as we have seen, proper application of statistical analysis requires that the underlying physical mechanisms be understood and accommodated. When not accommodated, the implied certainty of results becomes invalid. We believe that there are four additional areas of uncertainty in the AS that argue against overanalysis of the data.

First, practical considerations resulted in the AS using groups of 60 Ss who were exposed to higher and higher energies (7 levels, 6, 12, 25, 50, and 100 impulses) until they failed, in which case they dropped to a less energetic level/number and continued to be tested. Such an arrangement means that an ear failing at level 6, 12 impulses, will not be tested at higher numbers of rounds at that level. But how should such a failure be considered in data analysis? Several choices are possible, but they involve irreconcilable conflict. Murphy et al. treated the higher exposures as if they consisted of subjects with the same likelihood of being damaged as the lower-exposure groups. By weeding out the susceptible Ss, the ears of the groups exposed at higher levels would consist of the less susceptible ears. From one perspective, such a position is indefensible. It would be difficult to argue persuasively that an ear showing unacceptable threshold shift to 6 impulses, for example, would not also show at least as great an effect to 50 or 100 impulses. Any conceivable DRC must embody such a provision. In fact, the AS design prohibited exposure to higher numbers of impulses once a failure had occurred because it was considered too great a risk. Murphy et al.'s choice resulted in fewer failures being counted, biasing their analysis in the direction of insensitivity.

The other dilemma is that if one propagates failures upward but does not test all the remaining population at the higher levels (as in some of the AS conditions), then statistics such as "percent failure" become biased in the direction of oversensitivity. For example, suppose 60 Ss were tested at 12 impulses and produced 1 failure. If that failure were propagated up to 100 impulses—but for the sake of argument, no one else was tested at that number—the failure rate at 100 impulses would be 100%, a probable overrepresentation of the true hazard to 100 impulses. There is no simple answer to the dilemma of how to propagate failures in determining risk. The uncertainty should simply be recognized as inherent in the AS data set.

Second, it is true that the AS was carefully conducted and is better documented than most studies. Nonetheless, critical gaps in the area of stimulus specification frustrate a full data analysis. As we noted earlier, many impulse waveforms have been made available, but no subject's exposure has been fully documented at any level. For most exposures to industrial-level noises, the lack of complete documentation is no problem. Sampling the stimulation is adequate because nothing that happens during any exposure interval can make that much difference to the final outcome. In the case of intense impulse noise, however, relatively small changes in HPD fit or a hot spot in the explosive cloud can produce a large effect in an ear. Were such "rare events" to occur, they could bias the data markedly. Some evidence indicates that they did occur.

Three specific examples of a rare event can be derived from the data that have been made available (Johnson, 1998). Consider the case of subject CEH2 in the 3M condition. Fortunately, for this S we do have several measures of the stimuli under the muff at several levels. For most levels, his exposure looked like that of others exposed at that level. However, at level 3, his data for three impulses (all we have) were clearly much more intense. Specifically, they were 3.2, 3.4 and 4.7 standard deviations above the rest of the Ss—this is statistically highly significant. As it happened, this subject passed this level, but it does demonstrate that unusually high exposures could have occurred in other cases and not have been documented.

Or similarly, consider the ear coded as BHM1 that had exposures (in ARUs or L_{AEQ8}) like the other ears in the group during tests with the intact muff in the 5-m condition, at least for the lowest six of the seven levels. At level 7, however, there was a difference. The distinctive exposure waveform we have for that ear at level 7 is plotted in figure 3, along

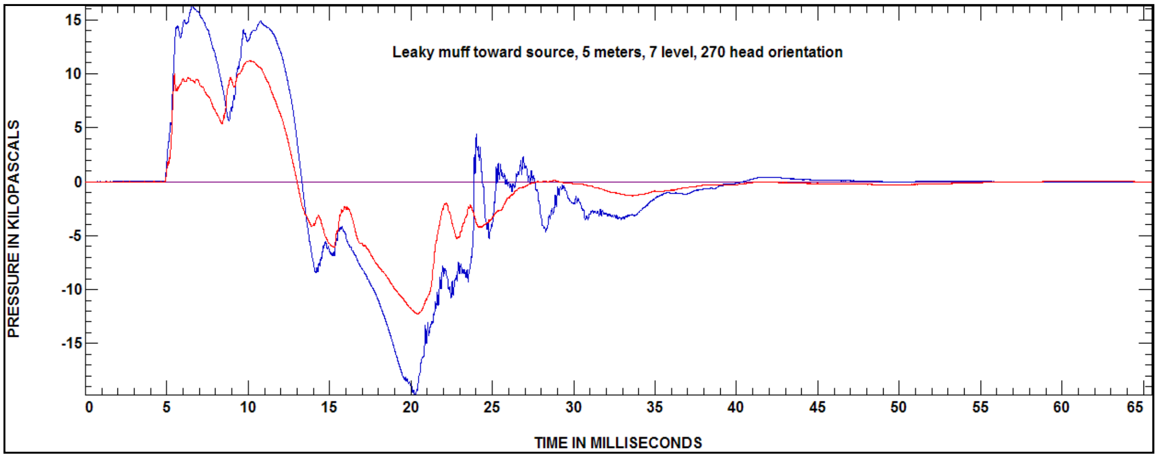


Figure 3. Two waveforms under the intact muff: 5-m condition, level 7, subjects BHM and BHM3. One had 20 ARUs and the more intense waveform had 106 ARUs.

with a typical waveform. In the figure we see that the peak pressures for one of the rounds is higher than the other for this condition and, more importantly, it shows oscillations at about 25 ms into the waveform. These oscillations are near atmospheric pressure; hence, the middle ear is operating more linearly (i.e., it is not peak clipping). In that case, the AHAAH model suggests that they could drive the ear effectively and result in more than 5× the hazard (106 vs. 20 ARUs). This effect can be seen in figure 3, in which the pressure history in air is plotted for one round, along with the growth of calculated hazard. In that figure it is apparent that about 70% of the hazard in ARUs occurred between 24 and 29 ms when the exposure waveform was near atmospheric pressure and the middle ear was free to move. The other ears in this group received about 18 ARUs per impulse. But BHM1 received 106 ARUs from this waveform, which is more than 7 standard deviations higher than the mean for the rest of the group. If the rest of the rounds were like this one, exposure for BHM1's ear would have been 648 ARUs for 6 rounds rather than 108 ARUs that the others received on average. A dose of 500 ARUs predicts that a susceptible ear would experience a C or an F in the AS. Or, put another way, the single more intense round produced essentially the same hazard as a six-round exposure for an average ear.

In that light, consider the case of subject DCE5. This S showed a conditional failure at level 1, 6 impulses, which would normally be interpreted as indicating a probable full failure at level 2, 6 impulses (and higher), or at level 1, 12 impulses (or more). In fact, such an interpretation of this S's susceptibility would be mistaken. Not fully trusting the data, the experimenters re-exposed him, and he ended up passing exposures up to 13 dB higher and finally failing at an exposure 15 dB higher. One can only wonder what rare event happened during the level 1 exposure. In fact, a recent analysis of the AS data set has shown that of 28 Ss showing conditional or full failure, a surprising 25 went on to pass at higher levels, 17 at 6 or more dB higher, and 5 at 12 or more dB higher (Price, 2010). These data either argue against traditional notions of susceptibility or raise the question of whether or not the true exposure has been accurately evaluated.

Third, in spite of the scope of the studies, there were very few cases in which a subject actually had a 25 dB or greater threshold shift (considered an audiometric failure). Even though there were over 250 subjects, given more than 2500 exposures, there were only about 30 audiometric failures. The lack of failure is informative, but it conveys limited information because it does not indicate just how safe the exposure was. From a statistical standpoint, it is clear that we are dealing with the upper limit of a distribution for which we possess limited theoretical insight regarding the underlying processes affecting it.

Fourth, in yet another area, the problem of data limitation is exacerbated by the desire of the experimenters in the AS to provide only “clean” data waveforms. If there were reason to believe that a particular impulse was not “good,” e.g., contained some artifact, it was edited from the data set in order to avoid confusion. It is true that an artifact obscuring the true wave shape might mislead the unwary. However, were all the waveforms available, the waveform from an overloaded microphone, for instance, would nonetheless be instructive in indicating a failed seal on the HPD, resulting in a truly higher exposure (even if it was not precisely specifiable).

In conclusion, we can only counsel restraint in the analysis and interpretation of these data, particularly with regard to drawing conclusions from statistical metrics that imply certitude when the underlying data have significant deficiencies. These deficiencies include (1) the indications that rare events may have affected the stimulation received by individual ears, (2) the relatively small number of significant threshold shifts, (3) the likelihood that a failure would be followed by passes at much higher levels and (4) the unfortunate lack of complete documentation of the exposure histories.

8. Incompatible Comparisons Yield Dangerous Consequences

Murphy et al. and Chan et al. (2001) have used an L_{AEQ8} measured to evaluate hazard from very intense impulses, such as PPLs well over 170 dB at the ear canal entrance. We believe conducting such an analysis implicitly advocates a very dangerous concept. It is true that the French use L_{AEQ8} as a measure for impulse noise, as long as the PPL does not exceed 160 dB. Nonetheless, the levels in the AS are much higher than those proposed as a critical level for the human ear where the loss processes become essentially mechanical rather than metabolic (Price, 1983). Physiologically, the ear goes from being tired out to being torn up—these are very different end points in a nominal 85-dB L_{AEQ8} exposure. Such an exposure at lower pressures and longer durations will be followed by a full recovery and can be repeated daily for many cycles; however, at higher pressures and shorter durations, it could be followed by immediate, permanent hearing loss. Obviously, an unqualified 85-dB L_{AEQ8} criterion does not have consistent meaning for hearing conservationists. This observation applies not only to the paper by Murphy et al., but also to all such considerations of an L_{AEQ8} measure at very high SPLs. As we have seen, the L_{AEQ8} measure misses important parts of the ear's response to very intense sounds. This can be seen dramatically in the appendix. Actually, a reasonable case can be made that even for lower intensities, a simple weighted energy measure misses important aspects of the ear's response, especially the protective effect of recovery periods during an exposure.

As important as this issue is, the dividing line between metabolic and mechanical loss processes in the human ear has not been well established empirically. The AS peak pressures were more than 60 dB in excess of those used to validate the A-weighted energy measure, an immense extrapolation. There is a paucity of human data on hearing loss in the intermediate part of this range, between about 115 and 160 dB. That being said, as we noted, France does use A-weighted energy as a standard for intense impulsive sounds with PPLs of 160 dB or less. We believe that it is fortuitous that such a measure "works" for a few rounds of exposure to rifle fire, which is primarily what has been tested.

If ears are protected during exposure to small arms fire (as they should be), the SPLs at the ear canal entrance will be in the 120- to 150-dB zone, which would seem to justify attention to studying the effects of such impulses on hearing. More work in this area is required.

9. Hazard as Evaluated by the AHAAH Model

In closing, we draw attention to Murphy et al.'s warned calculation with the AHAAH model for audiometric failures, in which the model was used almost as intended (their figure 10). Because the AHAAH model, as they used it, predicted hazard specifically for the 95th percentile ear, the model did correctly predict all the true failures and erred slightly in the direction of oversensitivity for a few cases. The overpredictions would have been even fewer if the other part of the dilemma noted earlier was accepted and upward propagation of failures allowed. This is in essential agreement with the earlier evaluation by Price (2007).

Murphy et al. argued that the analysis by Price (2007) of impulses other than the AS data set was "flawed" and the conclusions were "irrelevant." Their contention deserves greater scrutiny. Specifically, the authors dismissed the small arms data from previous studies: "The meta-analysis conducted by Price (2007b) is thought provoking, but flawed. The AHAAH model requires waveform data to analyze the risk of a specific impulse. Many of the exposures in Price's analysis did not have the actual waveforms from the exposures reported. Price analyzed waveforms that were collected in similar conditions and from similar weapons in several cases. If the details of the waveform are critical to an accurate evaluation, then conjectures of the discrimination and superior performance of any model are irrelevant."

In fact, Price (2007) noted the difficulties and limitations in analyzing studies in which conditions and measures were not identical. But when they are all that is available and there is a need to understand the phenomena they examine, it is important to find legitimate ways to glean as much information from them as possible (hardly an irrelevant endeavor). In addition to the 53 conditions for the AS, Price (2007) analyzed an additional 11 studies and discussed 6 more interesting incidents. For the small arms studies (a critical subset of the available human data), 6 studies were analyzed in which 229 Ss had been carefully tested. The waveforms for these analyses were made from the same type of weapon used in the original studies and recorded in similar circumstances (often by the same person who had made the original measurements). Note that when small arms fire combat-loaded rounds, the result is highly repeatable. Manufacturing tolerances are close, and such rounds can almost serve as calibration standards.

Murphy et al., having dismissed waveforms recorded from the same weapon used in previous tests as irrelevant, were able, in the case of the AS data, to accept substitute waveforms in their analysis of the AS data. For one condition, the data recorded on the subjects was lost, and the waveform recording done during the preliminary tests in which the experimenters stood in for the Ss was all that were available. We agree with Murphy et al. that using these data was in the best interests of preserving information, yet we remain baffled that at the same time they deemed the small arms waveforms "irrelevant."

Also, in the interest of scientific balance, the AHAAH model does correctly address not only the AS data set, but also the existing small arms data (the entire range of gunfire impulses) without adjustment. Furthermore, the AHAAH model is theoretically based and specifically includes the stapes nonlinearity. Thus, unlike simple correlational models, AHAAH's theoretical foundation reduces the risk of extrapolations to impulses not specifically tested.

10. Summary Comparisons*

The discussion in this report has tried to focus on the most critical issues raised in the paper by Murphy et al., find areas we find technically invalid, and seek other points with which we can agree. The authors claimed to evaluate the performance of MIL-STD-1474D, L_{AEQ8}, and the AHAAH model as they predicted outcomes on the AS data set. Their approach overlooked the following critical invalidating issues for most of these comparisons.

- MIL-STD-1474D: calculations are invalid because of the confounding effects of the unique nonlinear protectors and cannot be extrapolated to other levels because of the nonlinearity of the stapes.
- L_{AEQ8} (free-field data): calculations are invalid because of the confounding effects of the unique nonlinear protectors and cannot be extrapolated to other levels because of the nonlinearity of the stapes.
- AHAAH (unwarned): application is invalid for Albuquerque data set (warned condition required), and the prediction of the population percentage affected is invalid (incompatible with the model's approach).
- AHAAH (warned): prediction of population percentage affected is invalid (incompatible with the model's approach).
- L_{AEQ8} (under protector): application of calculated L_{AEQ8} to other levels is questionable because of stapes nonlinearity.

On the other hand, there were a few points where their analysis did support valid inferences, which, unfortunately, they did not discuss. These points include the following:

- L_{AEQ8} (under protector) does demonstrate that, for the AS data, a potential criterion value for L_{AEQ8} near 110 dB is greatly in excess of 85 dB (generally accepted as valid level).
- The AHAAH model, warned calculation, did rank hazard acceptably for the AS data set and, without change, would also do so for small arms fire.
- Development of a comprehensive DRC for intense noise needs more research in the pressure regime between 115 and 160 dB.

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* When we compared the free-field pressure measures reported by Murphy et al. (their tables 5–8) with both our own analyses of the same data set and with the report by Patterson et al. (1997), we discovered that our measures agree with Patterson's and that on average, the peak pressures measured by Murphy et al. were about 5–7 dB too low. Given the foregoing arguments regarding the invalidity of the analysis with free-field pressure, the issue of exact peak pressure in the exposure is, of course, moot. In the interest of clarification of scientific discourse, however, we include this note.

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Appendix. Comparison of A-Weighted Energy and the AHAA Model in Predicting Damage to the Cat Ear

The organizing effect of a theory can be easily seen in the data from studies using the cat ear exposed to impulse noise–producing damage.[1] A dozen different exposures had been used on groups of 10 animals and threshold shift measures made electrophysiologically. Air bags, primers, and rifle impulses were sources, and numbers of impulses varied from 1 to 6 to 12 to 50.

In figure A-1 we plot mean threshold shifts at 30 min as a function of the A-weighted energy in the exposure for 12 experiments with the cat ear exposed to impulsive sounds. Each data point represents the mean loss at the frequency showing greatest loss for both ears of 10 cats. The trend line is fitted to the exposures with the primer (triangular data points). This use of A-weighted energy with the cat ear is not strictly justified; A-weighting generally reproduces the sensitivity of the human ear. The sensitivity of the cat ear is generally like that of the human in terms of the low and high frequency slopes. It is more sensitive than the human ear in the mid-range and tuned a little higher. But the general shape is the same, so if A-weighting is a useful concept in the rating of hazard, it should help make sense of the data.

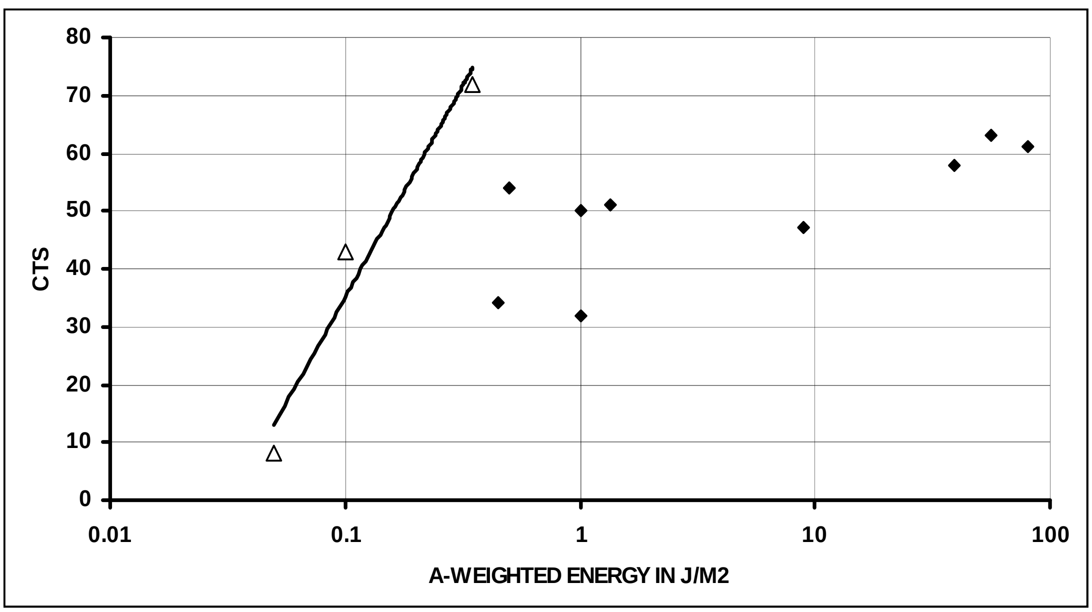

Figure A-1. Mean compound threshold shifts (CTSs) (threshold shifts measured at 30 min) for 12 experiments, with the cat ear exposed to impulsive sounds as a function of the A-weighted energy in the exposure.

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[1] Price, G. R. Impulse Noise and the Cat Cochlea, 2003. http://www.arl.army.mil/ARL-Directorates/HRED/AHAAH (accessed August 2010).

It is easy to see that A-weighted energy does a very poor job of organizing the data. For the primer data—triangular symbols with a line of best fit—there is clearly a linear relationship to energy. However the rest of the data points wander with a slight upward tilt for about 30 dB of energy increase.

Consider next the same threshold shift data when analyzed with the precursor cat version of the Auditory Hazard Assessment Algorithm for Humans (AHAAH) model (same algorithms, just electroacoustic values suited to the cat ear, AHAA), plotted in figure A-2. Each data point represents the mean loss at the frequency showing greatest loss for both ears of 10 cats. The trend line represents the least squares fit to all the data.

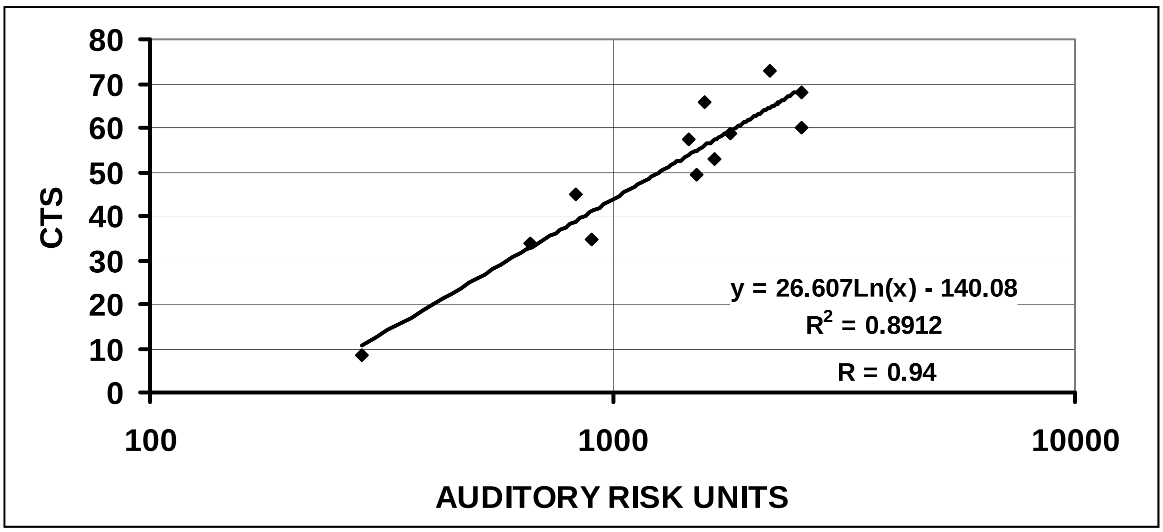

Figure A-2. CTS (threshold shifts measured at 30 min) for 12 experiments, with the cat ear exposed to impulsive sounds as a function of the auditory risk units calculated with the AHAA model of the cat ear.

The data now fall in a remarkable orderly line and can be seen as highly correlated with the model's assignment of risk units. The correlation is 0.94, which implies that there is little variance left to explain. The AHAA for the cat ear clearly operates as an explanatory mechanism.

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